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13. ABSTRACT *(Maximum 200 Words)*

A sample of a subsoil of the Pleasanton series was excavated and brought to the laboratory, where acoustic measurements were made over a frequency range from 0.5 to 10 kHz an under three conditions: dry (the original condition of the soil in its natural environment), partially saturated, and fully saturated. Additionally, measurements in the fully saturated soil were made at two different levels of compaction, or density.

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13 October 1994

Final Report

Measurements of Low-Frequency Acoustic Attenuation in Soils

Prepared by:

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Contents

Abstract

In support of efforts by the U.S. Army Construction Engineering Research Laboratory to design an acoustic subsurface imaging system, a set of experiments was conducted in which the attenuation and the velocity of propagation of acoustic waves traveling through a subsoil were measured.

A sample of a subsoil of the Pleasanton series was excavated and brought to the laboratory, where acoustic measurements were made over a frequency range from 0.5 to 10 kHz and under three conditions: dry (the original condition of the soil in its natural environment), partially saturated, and fully saturated. Additionally, measurements in the fully saturated soil were made at two different levels of compaction, or density.

In dry soil, the attenuation of the acoustic signal was extremely pronounced, and the velocity of propagation was low. Attenuation improved when the soil was partially saturated, and propagation velocity increased almost four-fold. There was no significant difference in the attenuation measured in partially saturated soil and that measured in fully saturated soil. Measurements in the fully saturated soil, however, were made at two different levels of compaction (86% and 93%). Unlike attenuation, the velocity of propagation was found to vary considerably depending on the level of compaction of the fully saturated soil.

Compaction, which affects both density and bulk modulus, appears to play a significant role in defining the speed at which acoustic waves propagate through soil. Any kind of relationship between either compaction or moisture content and the attenuation of acoustic signals is less evident. The rate of attenuation is markedly different in dry and partially saturated soils, but there are only minor differences in attenuation in partially and fully saturated soils.

1 Introduction

This report describes the results of experiments conducted to measure the attenuation and the velocity of propagation of acoustic waves in a clay subsoil. Measurements were made over a frequency range of 1 to 10 kHz under three conditions: dry soil, partially saturated soil (containing approximately 50% moisture) and fully saturated soil. Additionally, measurements in the fully saturated soil were made at two different levels of soil compaction.

These measurements were made in support of the U.S. Army Construction Engineering Research Laboratory's efforts to design an acoustic subsurface imaging system which would ideally be capable of a range resolution of approximately 15 cm to a depth of 2 m. Such a system can be an effective alternative to ground-penetrating radar (GPR) systems in cases when soil conditions are known to degrade the performance of GPRs.

2 Soil Description

The soil used in the experiment came from a region of Santa Clara County, California, that lies within the city of Saratoga. A description of the soils typically found in this area was provided by the U.S. Department of Agriculture's Soil Conservation Service. The predominant soil type falls within the Pleasanton series, which consists of well-drained soils and moderately fine-textured subsoils. The surface soil, which averages 12 to 20 in. in thickness, is a slightly acidic, grayish-brown loam or gravelly loam. The first substratum, 24 to 30 in. thick, is a neutral, dark grayish-brown, gravelly clay loam; the second substratum is a neutral, yellowish-brown, sandy clay loam that rests on a gravelly alluvial material extending to an undetermined depth. Although the soil for this experiment came from an excavation that was only 18 to 20 in. deep, its color and geologic characteristics are consistent with the Soil Conservation Service's description of the second substratum.

Before the experiment, the soil was passed through a 0.25-in. screen to remove any large gravel. It was then analyzed by Soil and Plant Laboratory, Inc., which described it as a sandy clay loam consisting of 51.8% sand, 24.8% silt, and 23.4% clay. The laboratory report is attached as Appendix A.

The soil's moisture content was then measured with a Delmhorst KS-D1 Digital Soil Moisture Tester that employed GB-1 gypsum soil blocks. In this test, moisture content is expressed as a percentage of the soil's maximum adsorption level, which is also the point at which the greatest compaction is reached. The optimum moisture content (point of greatest compaction) of the type of soil in question is approximately 11.2% by weight. The soil sample that was brought to the laboratory had been sun-dried in its natural environment for an undetermined period; it yielded a moisture content of 0. The

soil was hand-compacted in the measurement container at 1- to 2-in. increments of depth, ensuring that it was compacted evenly throughout the sample. The first acoustic measurements were made at this point. The soil was then removed from the measurement container, and water was added to bring it to a partially saturated state. The soil-water combination was mixed with a shovel to ensure consistency throughout the sample. When the desired level of moisture had been achieved (as measured by a moisture sensor), the soil was replaced in the measurement container and again compacted at 1- to 2-in. increments of depth. The second set of measurements was made at this point. Then, more water was added to bring the soil to a fully saturated state; the same procedure for mixing and compaction was followed. Acoustic measurements in the fully saturated soil were made at two different levels of compaction, 86% and 93%. (The soil was removed from the container and re-compacted between these two measurements.) The compaction measurements were done by American Soil Testing, Inc., which used a nuclear probe to measure both density and moisture. The laboratory reports on the two tests conducted on the fully saturated soil are attached as Appendix B.

3 Experiment Setup

Figure 1 shows the experiment setup. The measurement container, cylindrical in shape, was 22 1/4 in. in diameter and 28 in. high. The sensors, AET-30 broadband accelerometers manufactured by Babcock and Wilcox, were packed into the soil inside this container; they were oriented vertically, one above the other, as shown. Delmhorst GB-1 gypsum soil blocks were also buried in the soil, near the edge of the container and at the same depths as the two acoustic sensors. The acoustic source was a 3-in., 40-1289A mid-range tweeter from Radio Shack. To improve acoustic coupling to the soil, the cone of the speaker was lightly packed with soil before being placed on the soil surface. To minimize potential reflection errors, there was a 2-in. layer of foam at the bottom of the container.
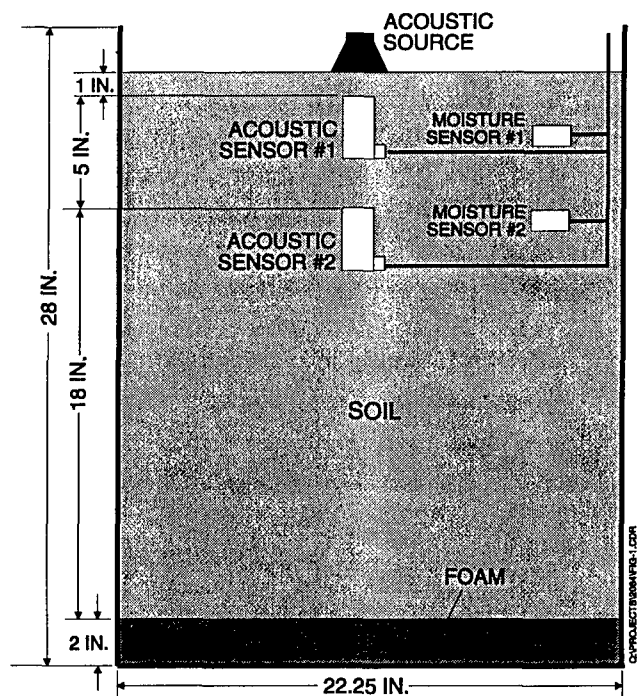

Figure 1. Experiment Setup.

Continuous-wave (CW) acoustic propagation measurements were taken at 451 frequencies within the 500- to 10,000-Hz range. These measurements were made every 5 Hz between 500 and 1000 Hz; every 10 Hz between 1 and 2 kHz; every 20 Hz between 2 and 4 kHz; and every 40 kHz between 4 and 10 kHz.

2

Time series data were collected from each of the sensors with the PC-based data acquisition system shown in Figure 2. A DDS-100 Digital Frequency Synthesizer was installed in the PC to generate CW signals to drive the speaker. The maximum power output of the DDS-100 is 0.5 W into 50 ohms. Sensor response was amplified by means of Panametrics 5660-C low-noise preamplifiers and filtered through Krohn-Hite 3342 low-pass filters with 20-kHz cutoff. The amplified sensor responses and the drive signal were digitized at a 44-kHz sample rate with an STI FLASH-12 A/D data acquisition card and then recorded to disk on the PC controller. A length of 16384 samples per channel was used for each frequency.
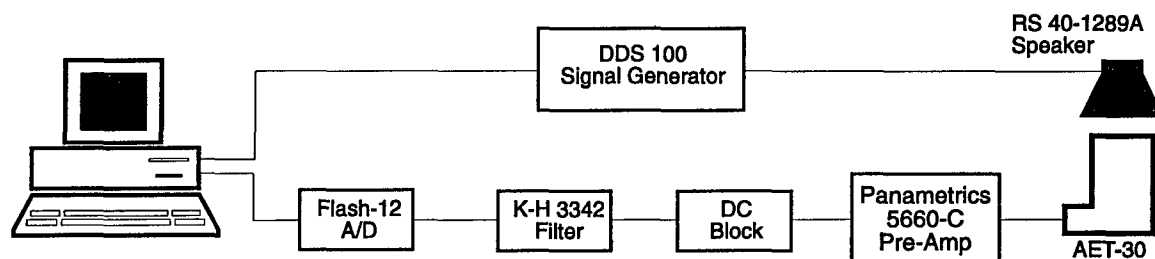
Figure 2. Data collection scheme.

A form of digital filtering was applied to all data as follows. A Hanning weighting was applied to the 16-k sample time series and the spectra were computed with an FFT. The power in the 7 frequency cells (9 Hz) centered on the peak were summed to calculate the recorded power in each channel. Recorded phase was defined by the center cell only. The signal power and phase received at each of the two sensors is defined relative to the drive signal generated by the DDS signal generator.

4 Results

Figure 3 shows the relative attenuation measured between the two sensors as a function of frequency in dry soil. Figure 4 shows the relative phase also as a function of frequency. Each plot is fitted with a least-squares regression line to determine the attenuation and propagation velocity, which is summarized in Table 1. For the dry soil, the least-squares fit was performed only on the attenuation data between 500 and 7800 Hz. In this case, attenuation was so severe that the response from the sensor located 6 in. below the source appeared to drop into the noise floor at about 7800 Hz. (The full 500- to 10,000-Hz data set for each sensor, as well as attenuation and phase plots, are included in Appendix C.) In addition, the numerous nulls in the sensor data below 1500 Hz (shown as peaks in the attenuation plot) combined with the high phase slope to cause phase unwrapping errors between 500 and 1500 Hz. Therefore, the phase data below 1500 Hz were not used.
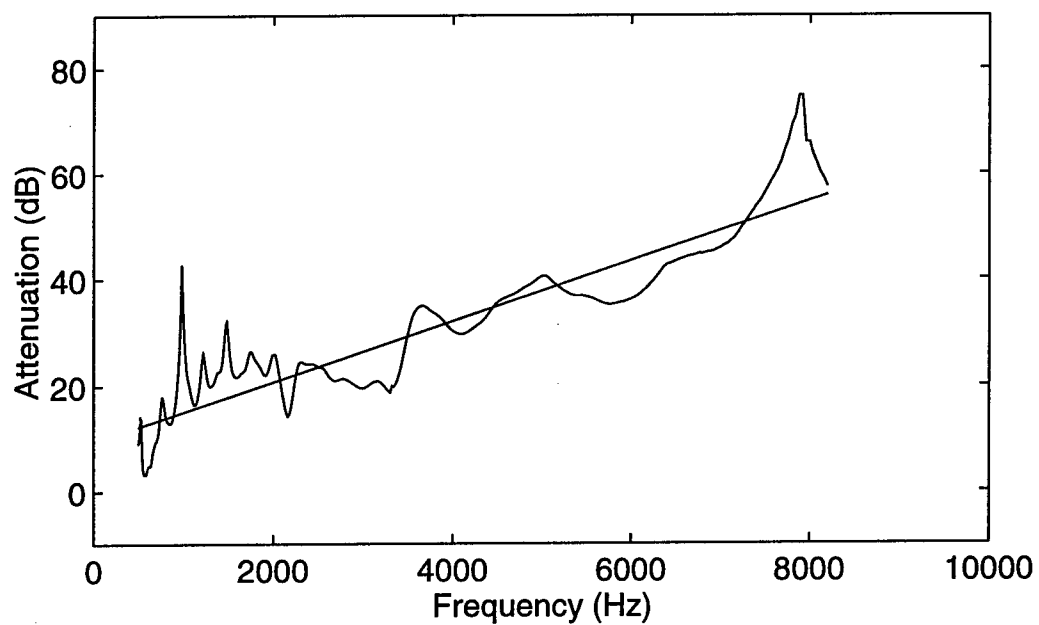
Figure 3. Relative attenuation between two sensors as a function of frequency (dry soil).
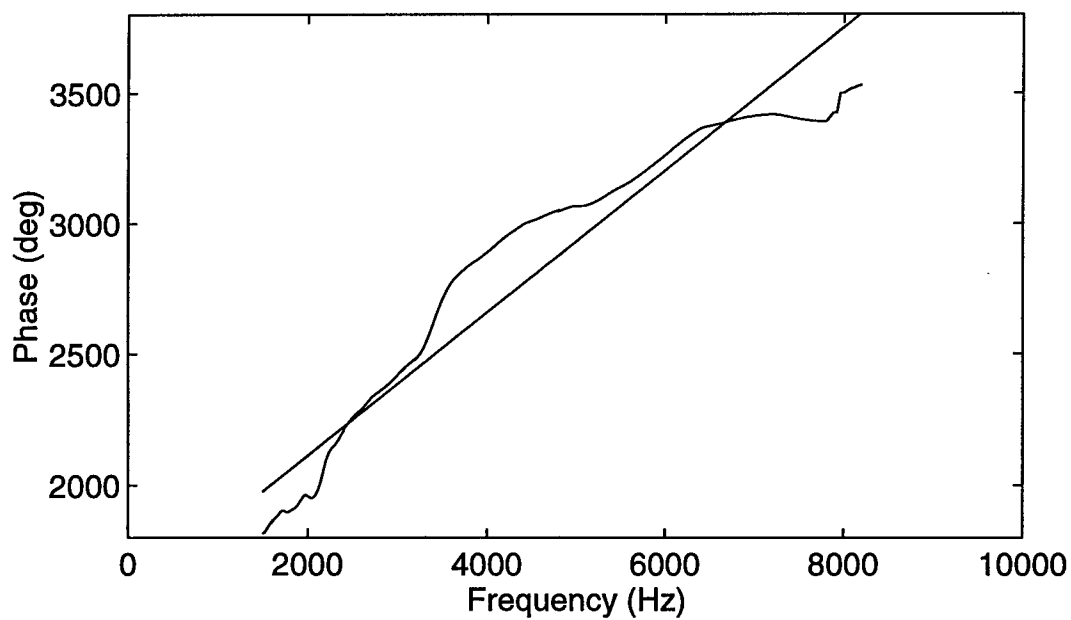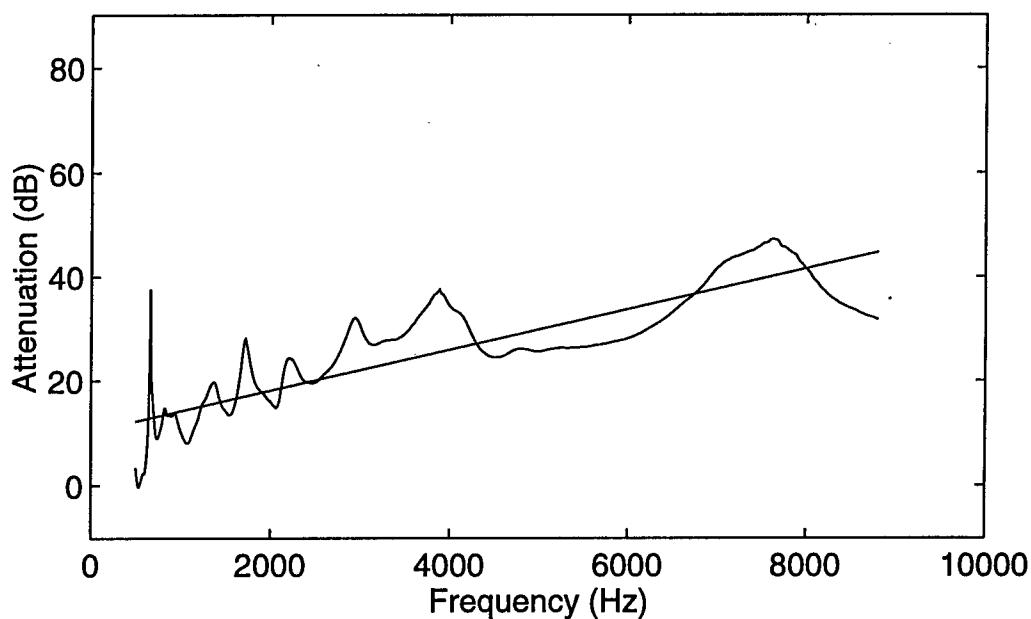

Figure 4. Relative phase as a function of frequency (dry soil).

Table 1. Summary of measured acoustic attenuation and propagation velocity for four soil conditions.

Soil Moisture Content	Soil Compaction	Attenuation (dB/m/Hz)	Propagation Velocity (m/s)
0.00%	NA	0.045	168
55.00%	NA	0.031	457
98.00%	86.00%	0.027	243
100.00%	93.00%	0.034	459

Similar data for the partially saturated soil are shown in Figures 5 and 6. Soil moisture level was measured to be 55% at both moisture probe positions, at the start and end of the acoustic data collection period. For this data set, acoustic data from 500 to 8800 Hz were used to generate the attenuation and velocity estimates.

Figure 5. Relative attenuation between two sensors as a function of frequency (partially saturated soil).
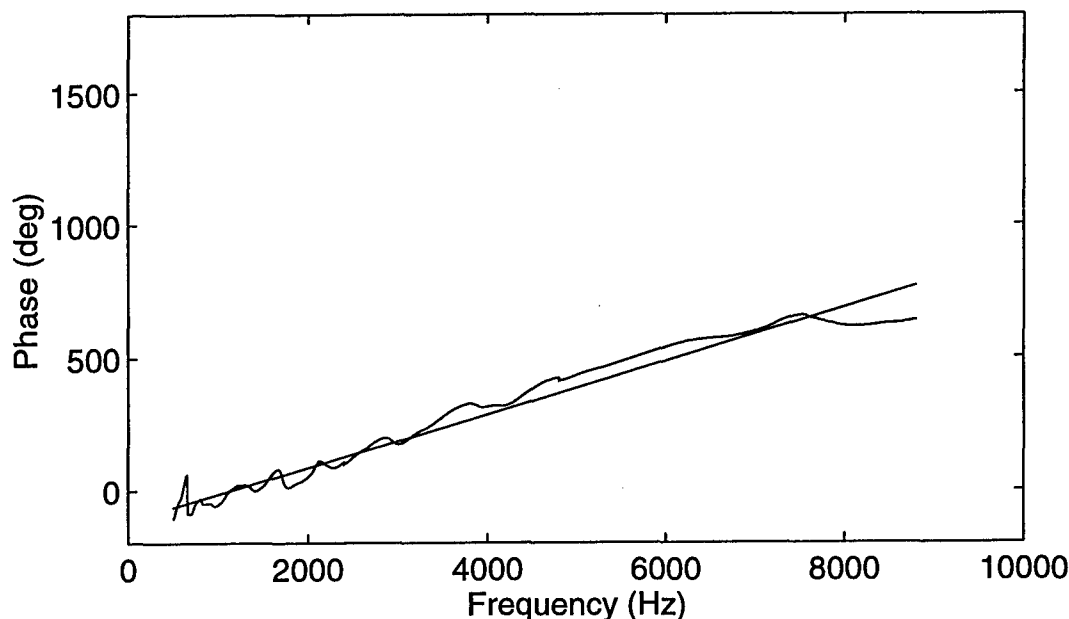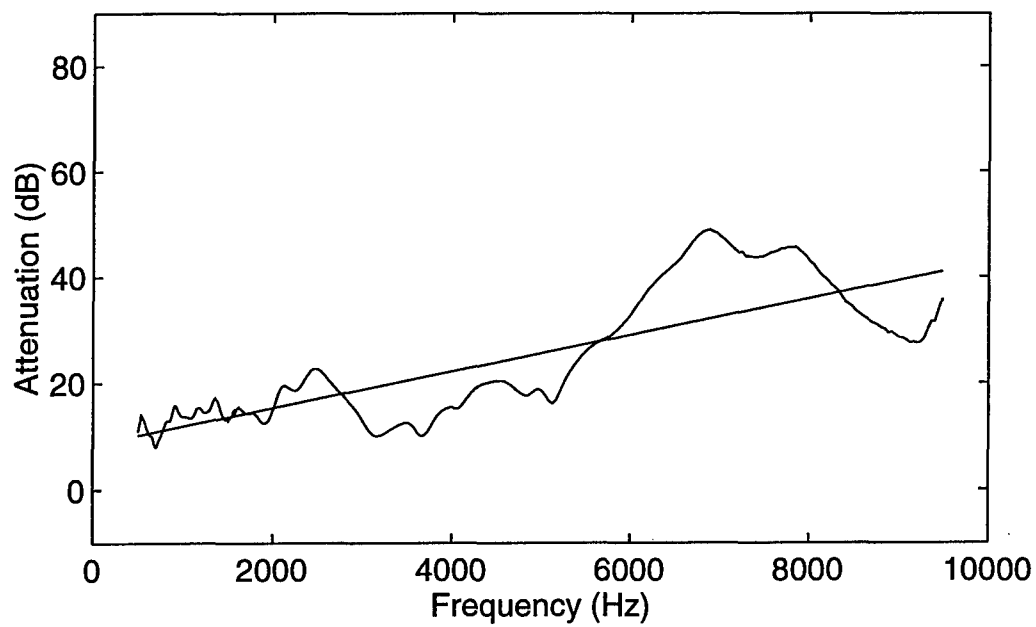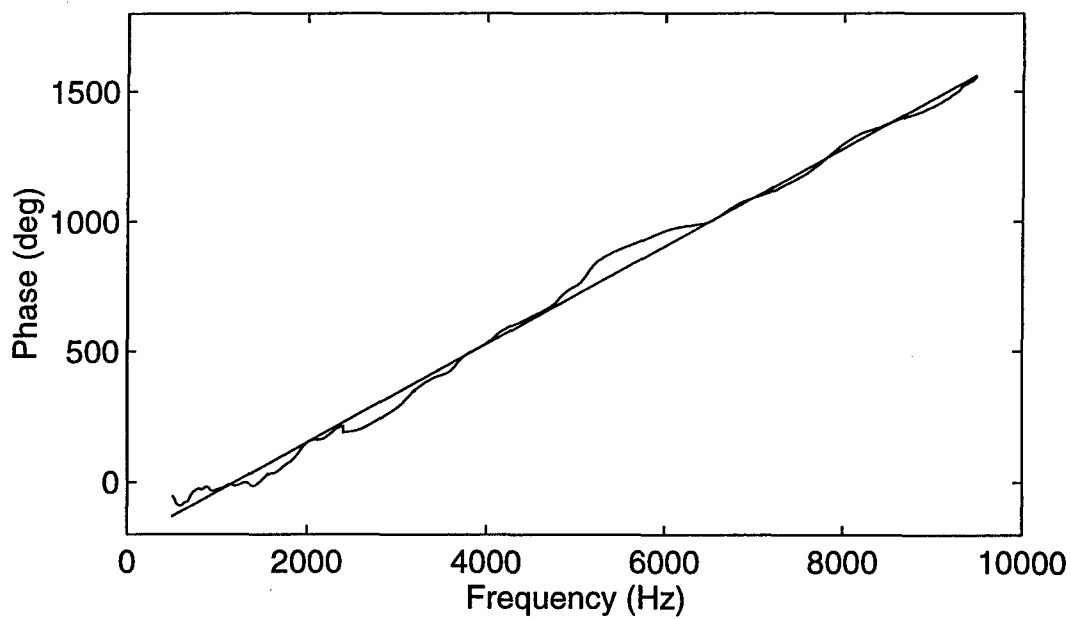
Figure 6. Relative phase as a function of frequency (partially saturated soil).

Attenuation and phase data for the fully saturated soil are shown in Figures 7 and 8. Soil moisture content was measured at 98%, and again this was consistent at both probe locations throughout the measurement period. The attenuation measured at the 98% moisture level was not significantly different from that measured at 55%; the propagation velocity, however, was significantly lower at 98% than it had been at 55%. This was inconsistent with expectations. In an attempt to resolve this inconsistency, an effort was made to assess the effect of soil compaction on propagation velocity. Thus, after the acoustic measurements had been completed, soil compaction tests were conducted on the undisturbed container. A nuclear probe indicated that soil compaction was 86% of maximum. The soil was then removed from the container and re-packed with the intent of achieving a higher compaction, which is believed to be more consistent with partially saturated soil conditions. Some additional water was mixed in to compensate for the drying that had occurred between tests. This time the nuclear probe indicated a compaction of 93% of maximum, and the Delmhorst probes indicated a moisture content of 100%. A second set of acoustic measurements was then made. The increased compaction caused a significant increase in the velocity of propagation with no significant change in the attenuation characteristics. The results are shown in Figures 9 and 10.

6

Figure 7. Relative attenuation between two sensors as a function of frequency (fully saturated soil compacted to a density of 86%).

Figure 8. Relative phase as a function of frequency (fully saturated soil compacted to a density of 86%).
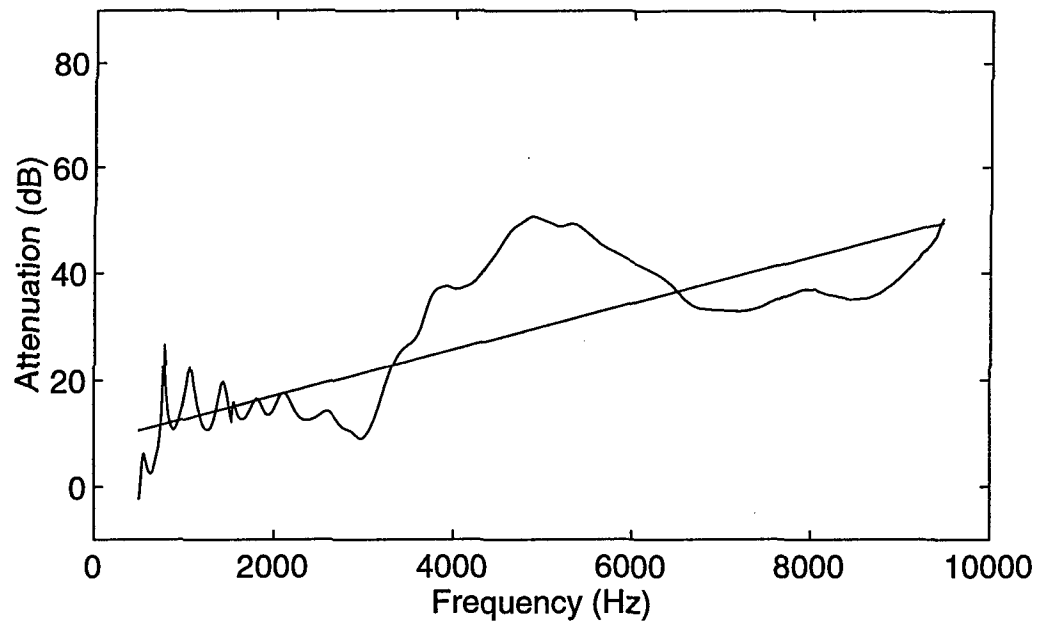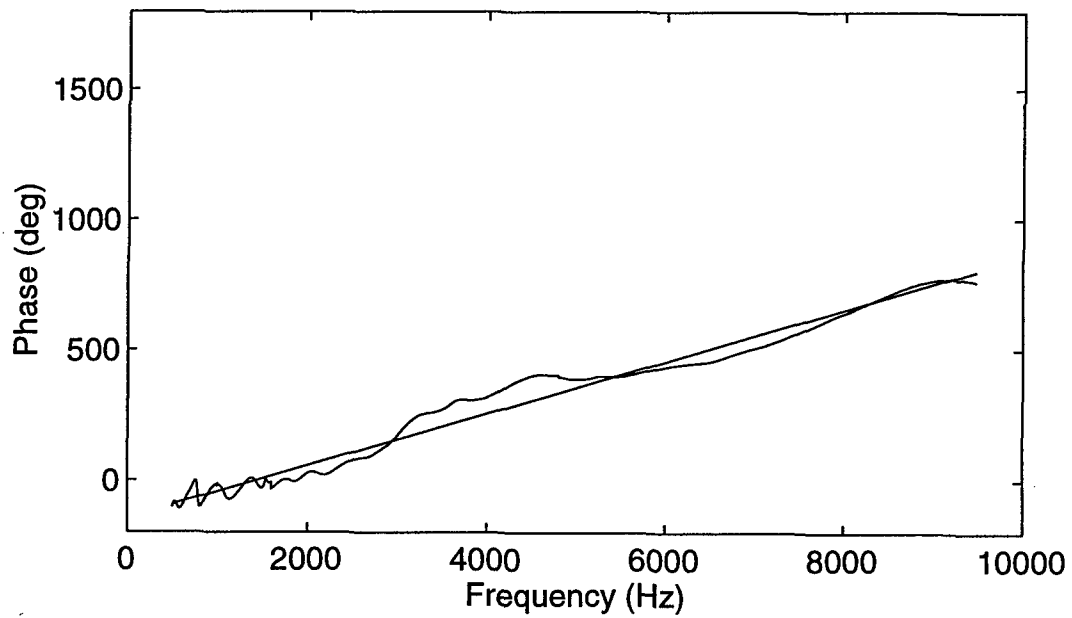
Figure 9. Relative attenuation between two sensors as a function of frequency (fully saturated soil re-compacted to a density of 93%).

Figure 10. Relative phase as a function of frequency (fully saturated soil re-compacted to a density of 93%).

5 Discussion

Three potential sources of error were recognized early in this project, and efforts were made to minimize their effects on the results of the experiment. The first is the calibration of the sensors. The sensors used in this project are resonant at 30 kHz. Their primary use is in acoustic emissions testing of materials, in which capacity they are used near resonance. Previous experience has indicated that these sensors respond well below resonance, but their response is nevertheless sensitive to their mountings. Because it was impractical to calibrate the sensors while they were packed in soil (as they were during the experiment), a scheme was developed whereby the sensors could be mounted to the back of a speaker for purposes of calibration. Because of the difference in mounting, the calibration data were not directly applicable to the measurements made in the soil, but these data did permit the selection of two sensors with very similar frequency response. From a set of 10 sensors that were considered, two were selected that yielded similar amplitude responses as a function of frequency.

The second potential source of error was from reflections of the acoustic signal. Reflections can occur when the signal bounces off the bottom or sides of the container and returns to the sensors. In CW measurements made during this test series, these reflections were able to artificially enhance or reduce the measured level of the acoustic return at each sensor. To evaluate the reflection environment in the test container, data were collected in which a pulse was generated with a given frequency. Pulses of 1 ms were generated at frequencies between 500 and 4000 Hz. At the low end of this band, reflections from the side wall of the container were evident approximately 10 dB below the level of the direct path signal. As the frequency increased, the amplitude of this reflection fell off sharply. This sharp decrease in amplitude is most likely due to the increasing directionality of the source with frequency. Reflections from the bottom of the container were not evident in any of the pulse data collected.

Finally, the fact that source directionality varied with frequency led to the placing of the acoustic sensors on the same axis as the source, so that both of these sensors would be located in a stable region of the source gain pattern. This, however, may have introduced shadowing of the lower sensor, a condition that may cause slight inflation of the attenuation estimates.

6 Conclusions

Based on the results of these experiments, soil compaction appears to play a significant role in defining the velocity of acoustic-wave propagation through soils. In fluids, acoustic propagation velocity can be calculated from [1]

$$c = \sqrt{\frac{B}{\rho}}$$

9

where c is the velocity of propagation, B is the bulk modulus, and ρ is density. The relative densities of the two fully saturated soils were measured, as was propagation velocity through these soils. The differences in density and velocity imply a change in the bulk modulus of the soil/water/air mixture equal to nearly a factor of 4. In granular soils, a change of this magnitude due to differences in compaction is not unreasonable [2].

Although the compaction of the dry and partially saturated soils was not measured, it is known, based on the compaction characteristics of soils, that the maximum compaction achievable in dry soil will be less than in partially or fully saturated soils. Therefore, in that moisture content defines the upper limit on soil compaction, it is expected that it would also define the upper limit on velocity of propagation. Since this study focused exclusively on moisture content at or below saturation, it is unknown if a relationship between compaction and propagation velocity holds true above 100% soil moisture content, where the maximum compaction achievable begins to decrease. It is likely that it does not, for the following reasons. Adding water to dry soil aids the compaction process by providing lubrication, and the moisture replaces air in the soil voids. After a high degree of saturation is reached, the water occupies space which could be filled with soil particles, and the amount of trapped air remains essentially constant. As the water replaces soil in super-saturated conditions, it might be expected that the acoustic propagation characteristics would tend toward that of water and thus the velocity of propagation would continue to increase despite decreasing soil compaction. This is evidenced by data on the velocity of propagation of acoustic waves through sea floors of both clay and silt; propagation velocity in these media are very close to that in seawater [1].

From the data collected in this experiment, a relationship between attenuation and (1) moisture content and (2) soil compaction is less evident. A comparison of dry and partially saturated soils showed that there was a significant change in attenuation between the two. However, partially and fully saturated soils show only minor differences in the frequency characteristics of the attenuation.

Finally, it should be noted that propagation characteristics may vary significantly depending on soil type. The soil used in the experiment is common in this area, but regions where the subsoil has a higher clay content may provide a better environment for the propagation of acoustic waves such as those generated by a subsurface imaging system. An experiment reported in the literature characterized the acoustic attenuation in a soil referred to as "pitcher's mound clay" as 0.0167 dB/m/Hz [3]. The measurements in that experiment were made between 300 and 4500 Hz, under unspecified conditions in terms of moisture content and compaction. The attenuation is significantly less than that measured in the sandy clay loam used in this experiment. This provides some insight into the variability in propagation characteristics that may be experienced with different soil types.

References

1. L. E. Kinsler, A. R. Frey, A. B. Coppens, and J. V. Sanders, *Fundamentals of Acoustics* (New York: John Wiley and Sons, 1982).

2. W. C. Teng, Foundation Design (Englewood Cliffs, N. J.: Prentice-Hall, 1962).

3. J. E. Huebler, B. K. Campbell, and G. K. Ching, "An Acoustic Technique for Tracing Plastic Pipe," *Materials and Evaluation* (August 1993): 900-908.

Appendix A

SOIL ANALYSIS

Soil and Plant Laboratory, Inc.

Santa Clara Laboratory
Lab No. 73152

2064

VISTA RESEARCH
100 View Street
Mountain View, CA 94041

SOIL APPRAISAL ANALYSIS
(AO3)

Samples Taken: Samples Rec'd: 9/ 7/94

These data are supplied without recommendation or comment by _____ Lori Littleford, Analytical Laboratory Director

Sam ple #	Half Sat. %	pH	ECe	Org %	Gravel Coarse Fine 5-12 2-5		Sand Very Coarse Coarse Med. to V. Fine 1-2 0.5-1 0.05-.5			Silt .002-.05	Clay 0-.002	USDA Soil Classification	Sample Description & Log Number
1					6.1	1.4	4.4	6.8	40.6	24.8	23.4	sandy clay loam	Existing soil 94-A28574 77

Half Saturation %=approximate field moisture capacity. Salinity = ECe(dS/m at 25 degree C). Gravel fraction expressed as percent by weight of oven-dried sample passing a 12mm (1/2 inch) sieve. Particle sizes in millimeters.

9/ 9/94

Appendix B

SOIL COMPACTION MEASUREMENTS

American Soil Testing, Inc.

Soil, Foundation and Environmental Engineers

File No. 94-429-T

Date: September 23, 1994

Vista Research, inc.

P.o. Box 998

Mountain View, CA 94042

Attention: Miss. Gill Harada

Subject: Compacted soil container

100 view Street

Mountain View, CA 94042

COMPACTION TEST RESULT

Dear Miss. Harada

Per your request, our firm has performed in place density testing services for the above mentioned project.

The results of our tests which we were performed, covering the last 8 inches from the top of.the container is shown in Table 1.

We performed Three (3) field density tests on the imprted soil in accordance with ASTM Test procedure D2922-81 (Nuclear Method) at the container on the compacted material.

To obtain the optimum moisture and maximum dry densities for the imported material, we performed one laboratory compaction test in accordance with ASTM D1557-78 procedure. (Modified Proctor Compaction test) .

TABLE I
SUMMARY OF FIELD DENSITY TEST RESULT

C

Test No.	Date of Test	Location or Elevation	Water Content Field	Moisture Field	Optimum Moisture Lab	Dry Density Field	Maximum Dry Density Lab	Relative Comp.	Recomended Relative Comp.	Soil Type & Remark
#	1994	Feet	pcf	(%)	(%)	pcf	pcf	(%)	(%)	
1	9/22/94	container	11.50	11.27%	11.20%	102.00	117.50	86.81%	?	Import silty sand
2	9/22/94	container	12.25	12.16%	11.20%	100.75	117.50	85.74%	?	Import silty sand
4	9/22/94	container	11.50	11.44%	11.20%	100.50	117.50	85.53%	?	Import silty sand
5										
6										
7										
8										
9										
10										
11										
12										
13										
14										
15										
16										
17										
18										

Project: Vista Resarch, Inc.

American Soil Testing, Inc.

Soil, Foundation and Environmental Engineers

UNDER ALL IS THE SOIL

4595 Cherry Avenue, San Jose, CA 95118 • (408) 978-8400 • Fax (408) 723-8245

File No. 94-429-T

Date: October 3, 1994

Vista Research, Inc.

P.O. Box 998

Mountain View, CA 94042

Attention: Miss. Gill Harada

Subject: Compacted soil container

                            100 View Street

                            Mountain View, CA 94042

                            COMPACTION TEST RESULT

Dear Miss. Harada

Per your request, our firm has performed inplace density testing services for the above mentioned project.

The results of our tests which we were performed, covering the last 8 inches from the top of the container is shown in Table 1.

We performed two (2) field density tests on the imported soil in accordance with ASTM Test procedure D2922-81 (Nuclear Method) at the container on the compacted material.

TABLE I
SUMMARY OF FIELD DENSITY TEST RESULT

C

Test No.	Date of Test	Location or Elevation	Water Content Field	Moisture Field	Optimum Moisture Lab	Dry Density Field	Maximum Dry Density Lab	Relative Comp.	Recomended Relative Comp.	Soil Type & Remark
#	1994	Feet	pcf	(%)	(%)	pcf	pcf	(%)	(%)	
1	9/30/94	container	13.75	12.70%	11.20%	108.25	117.50	92.13%	?	Import silty sand
2	9/30/94	container	14.50	13.18%	11.20%	110.00	117.50	93.62%	?	Import silty sand

Project: Vista Research, Inc.
100 View Street, Mountain View, California
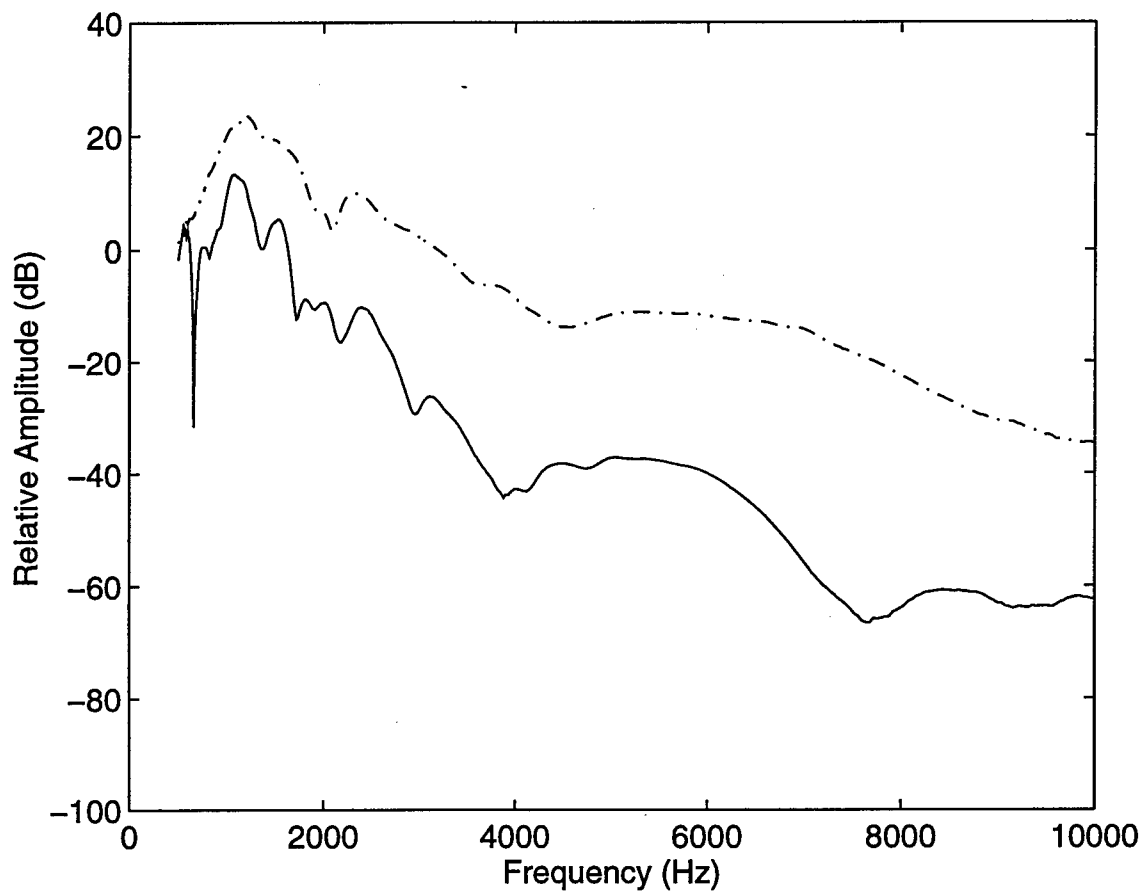
Appendix C

ACOUSTIC PROPAGATION DATA
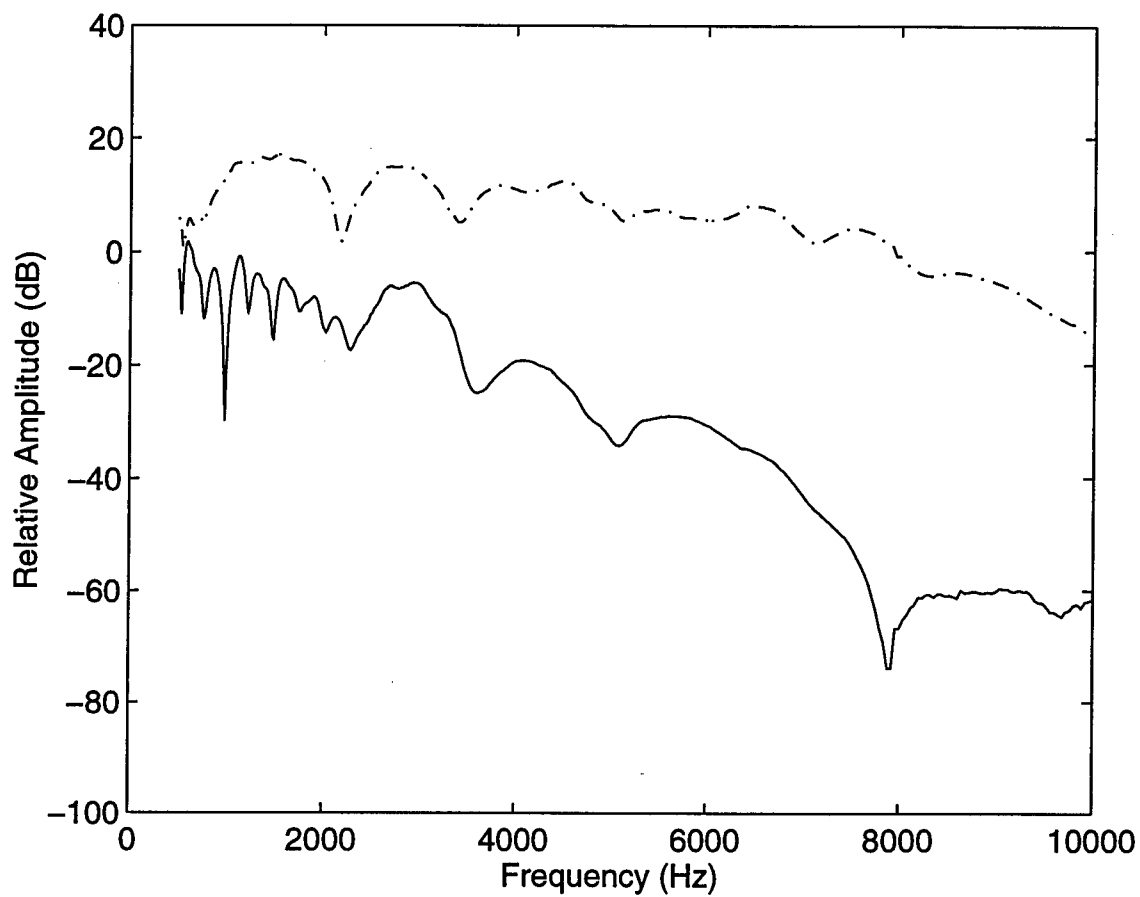
Figure C-1. Sensor amplitude vs. frequency for dry soil. The dashed line indicates the sensor located 1 in. from soil surface. The solid line indicates the sensor located 6 in. from soil surface.
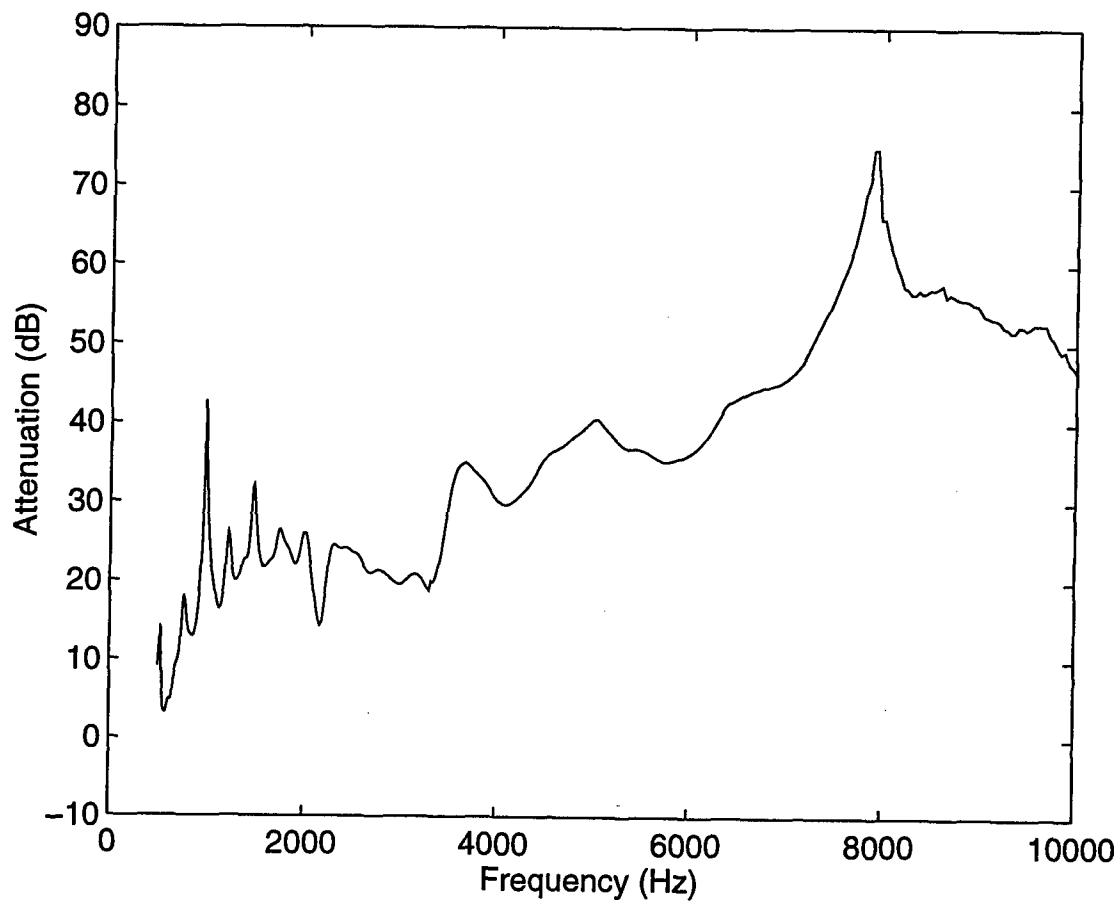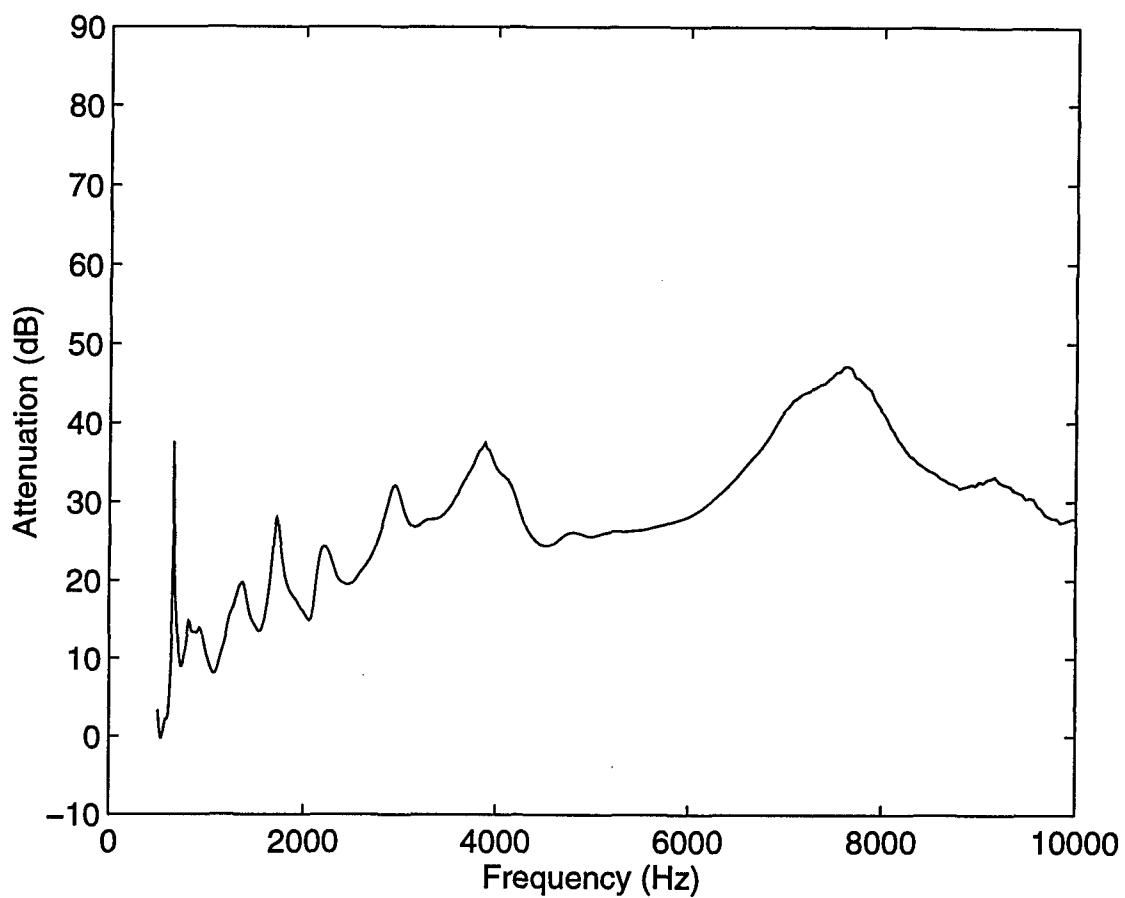
Figure C-2. Attenuation vs. frequency for dry soil. Attenuation is relative between two sensors spaced 5 in. (0.127 m) apart.
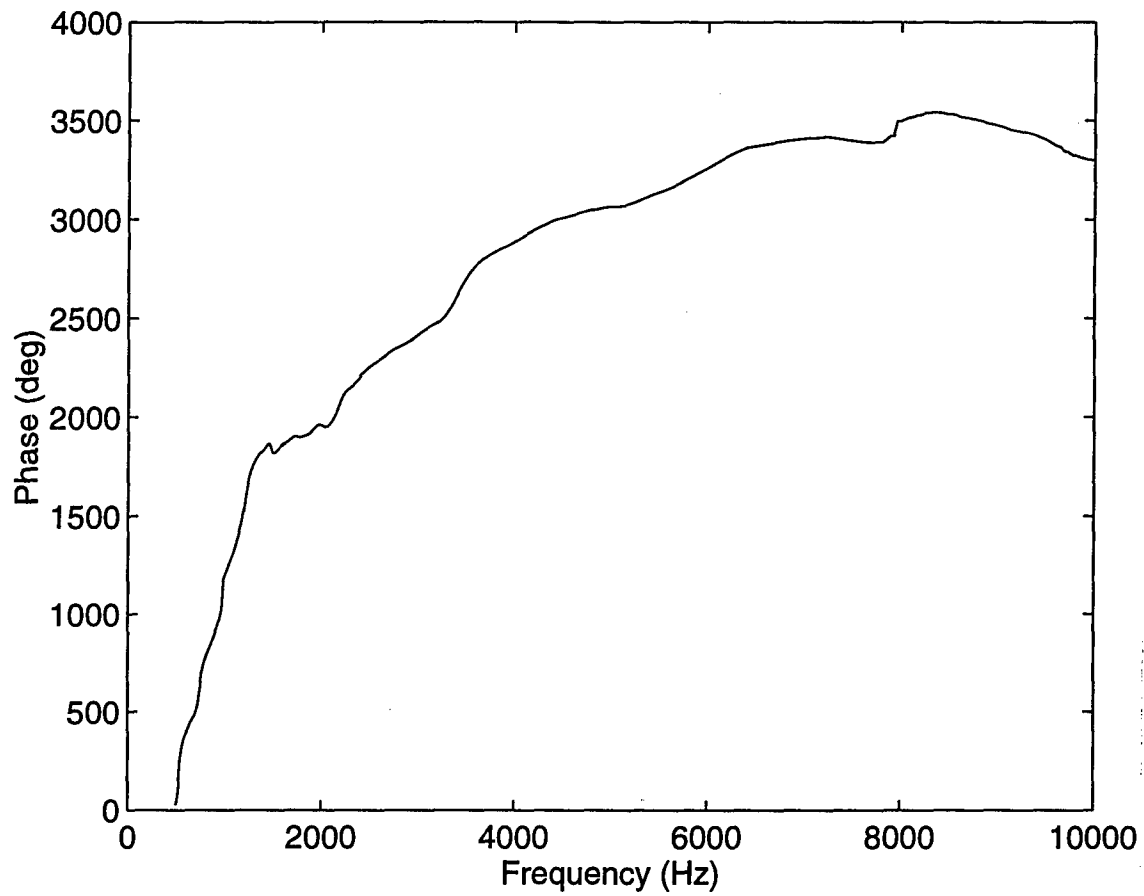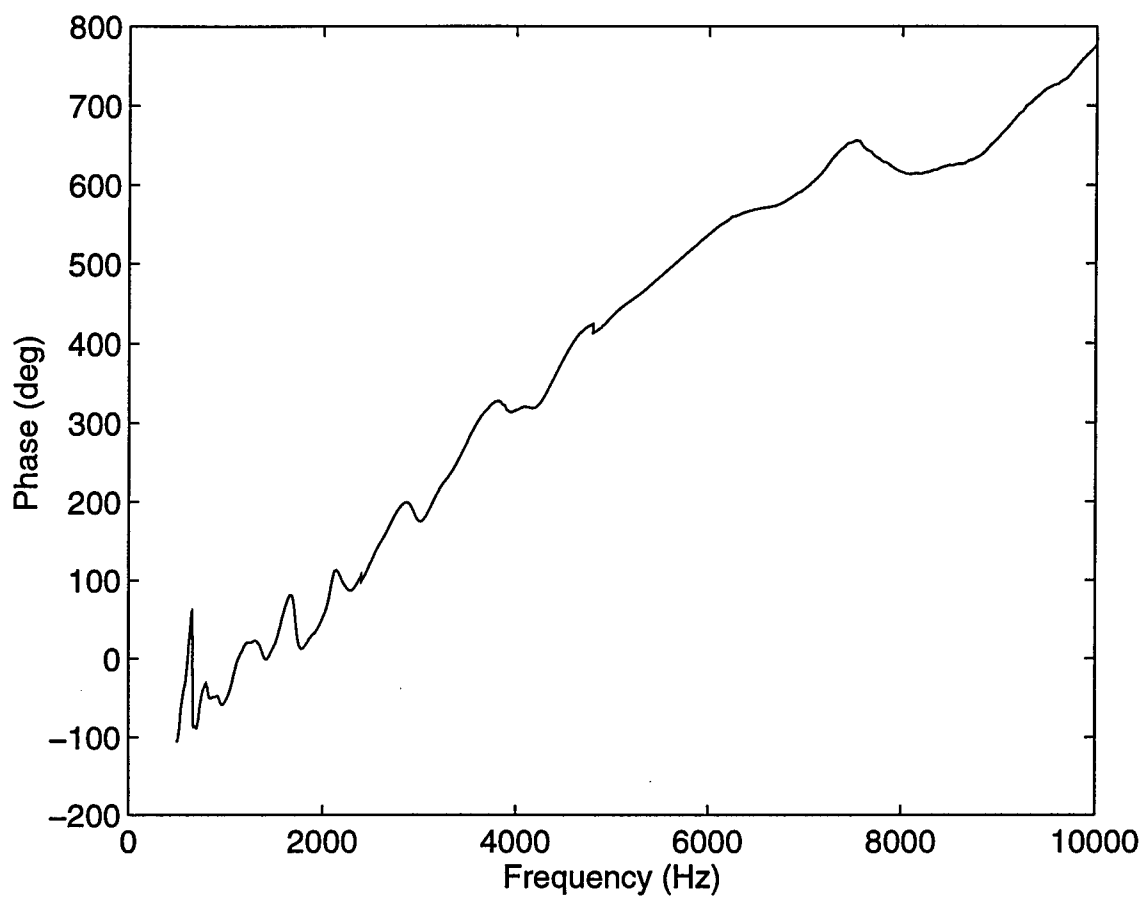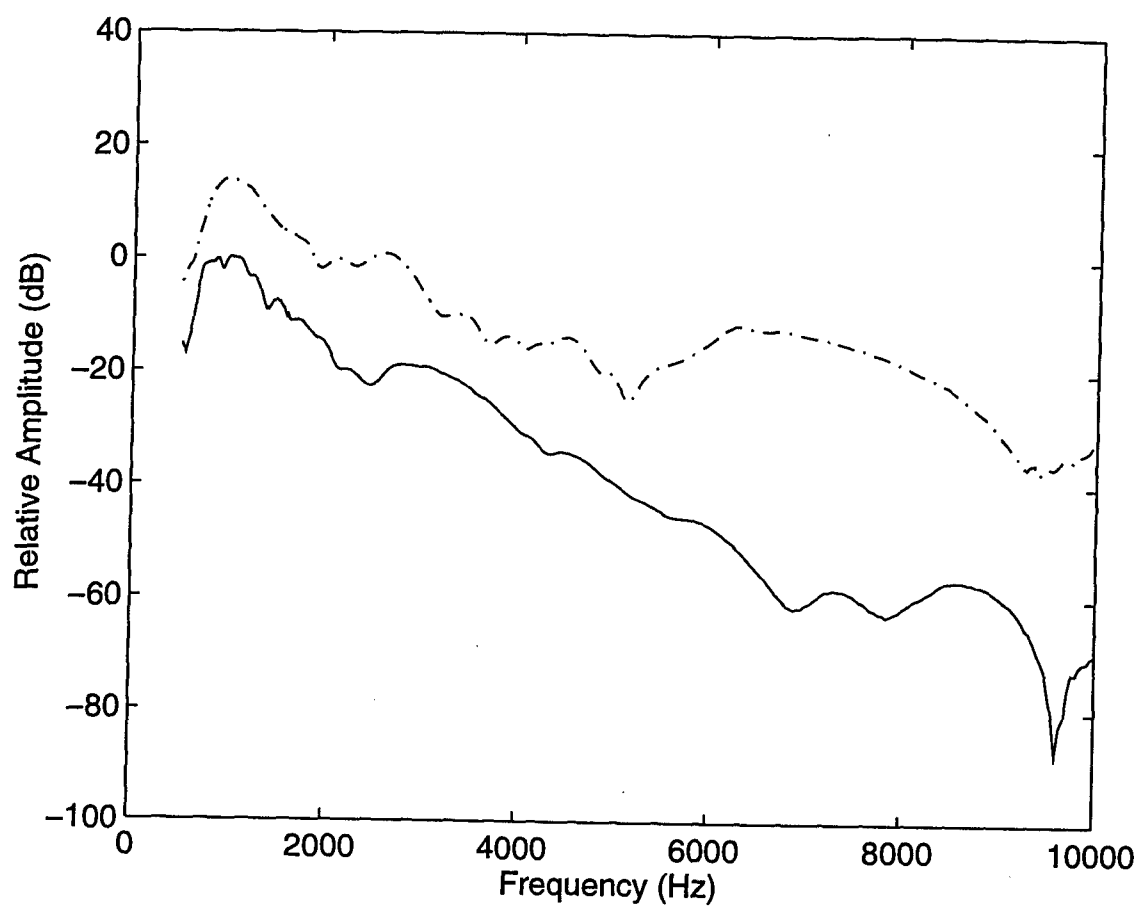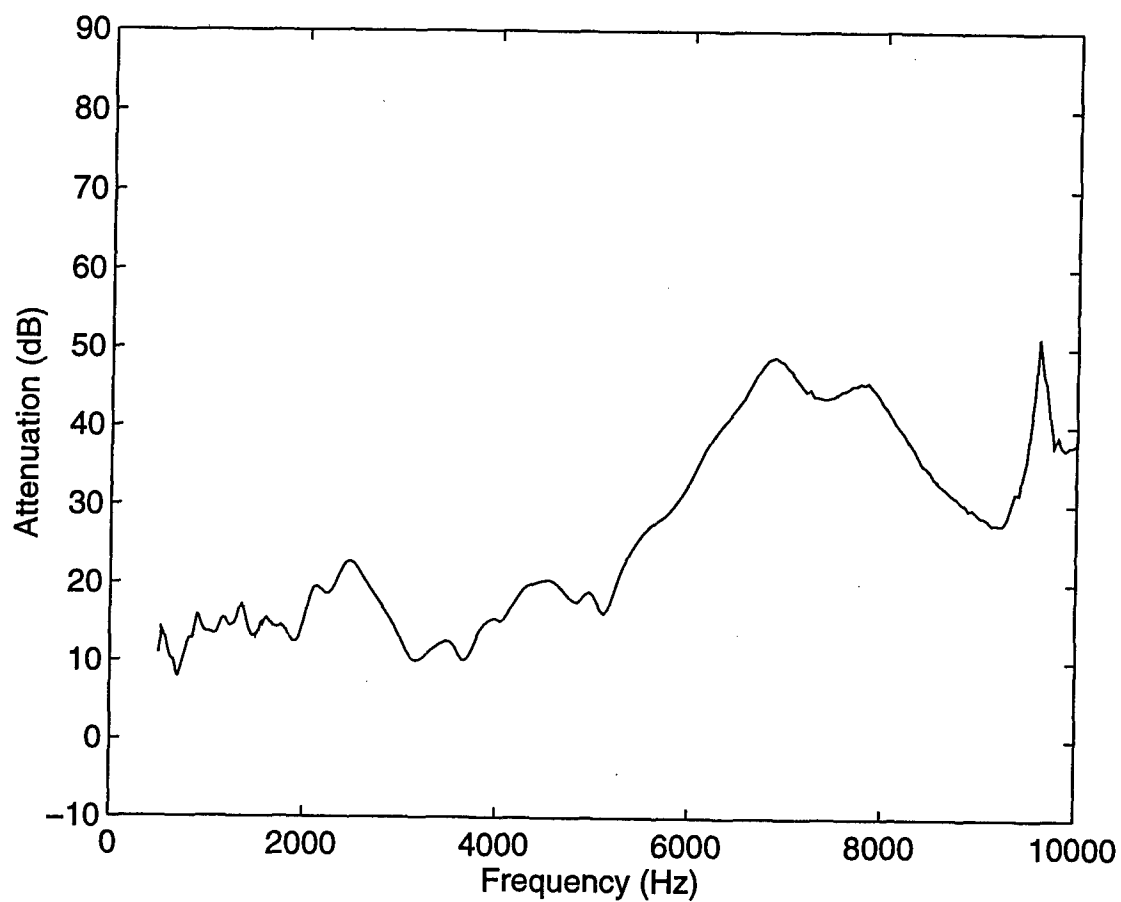
Figure C-3. Phase vs. frequency for dry soil. Phase is relative between two sensors spaced 5 in. (0.127 m) apart.

Figure C-4. Sensor amplitude vs. frequency for partially saturated soil. The dashed line indicates the sensor located 1 in. from soil surface. The solid line indicates the sensor located 6 in. from soil surface.

Figure C-5. Attenuation vs. frequency for partially saturated soil. Attenuation is relative between two sensors spaced 5 in. (0.127 m) apart.

Figure C-6. Phase vs. frequency for partially saturated soil. Phase is relative between two sensors spaced 5 in. (0.127 m) apart.
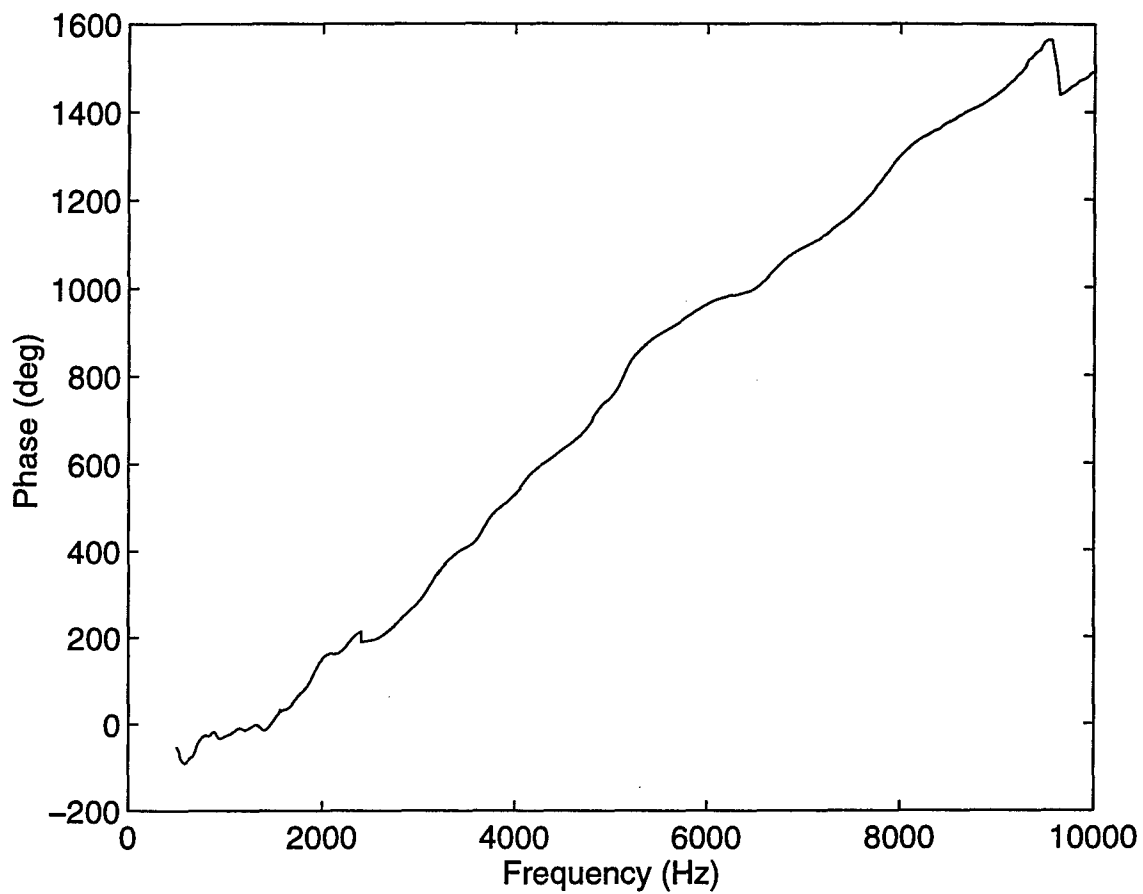
Figure C-7. Sensor amplitude vs. frequency for fully saturated soil at 86% compaction. The dashed line indicates the sensor located 1 in. from the soil surface. The solid line indicates the sensor located 6 in. from the soil surface.
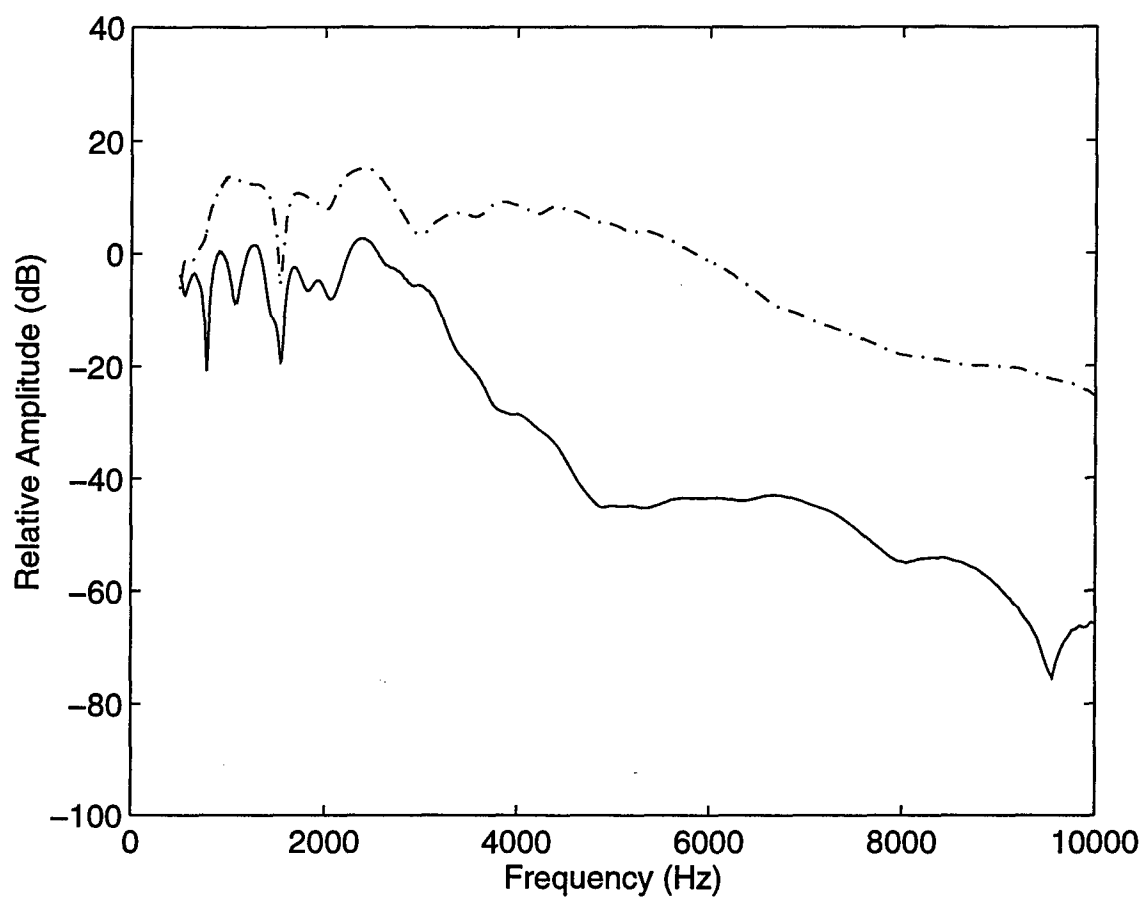
Figure C-8. Attenuation vs. frequency for fully saturated soil at 86% compaction. Attenuation is relative between two sensors spaced 5 in. (0.127 m) apart.
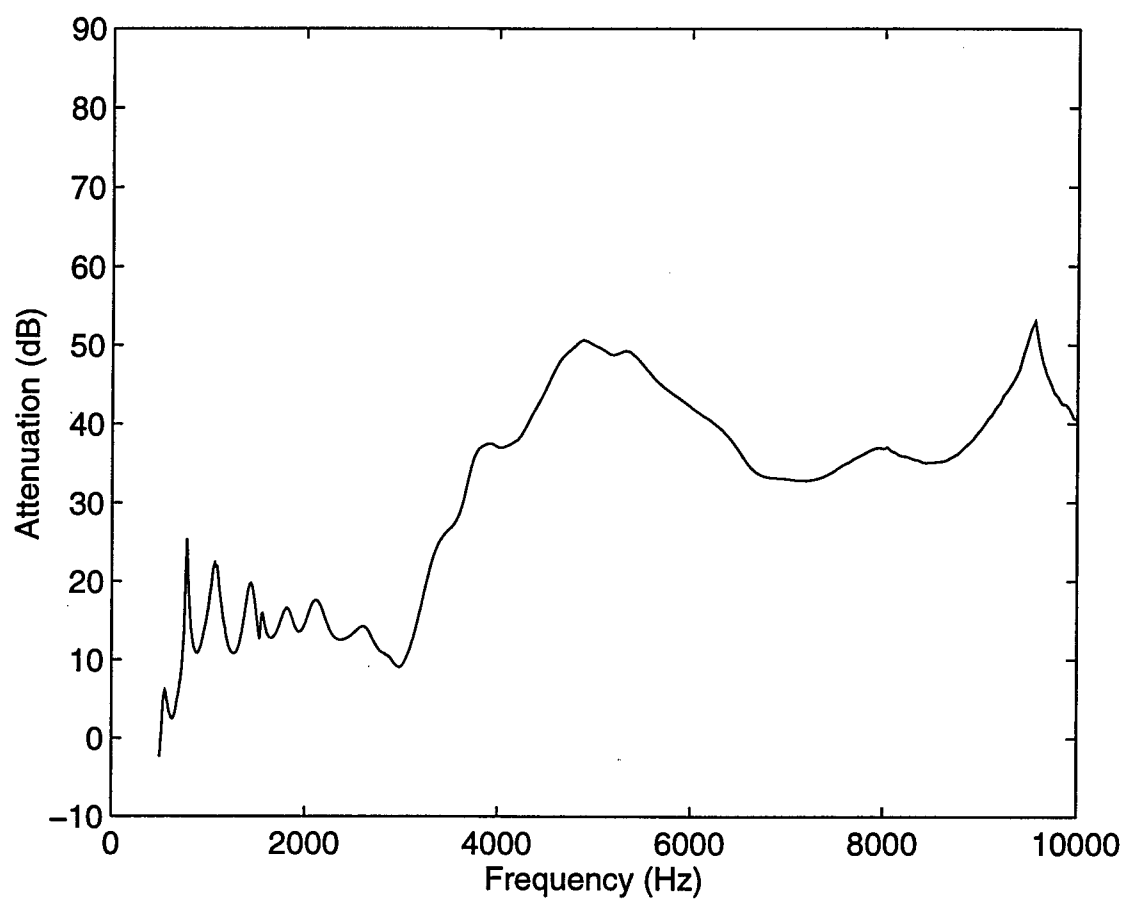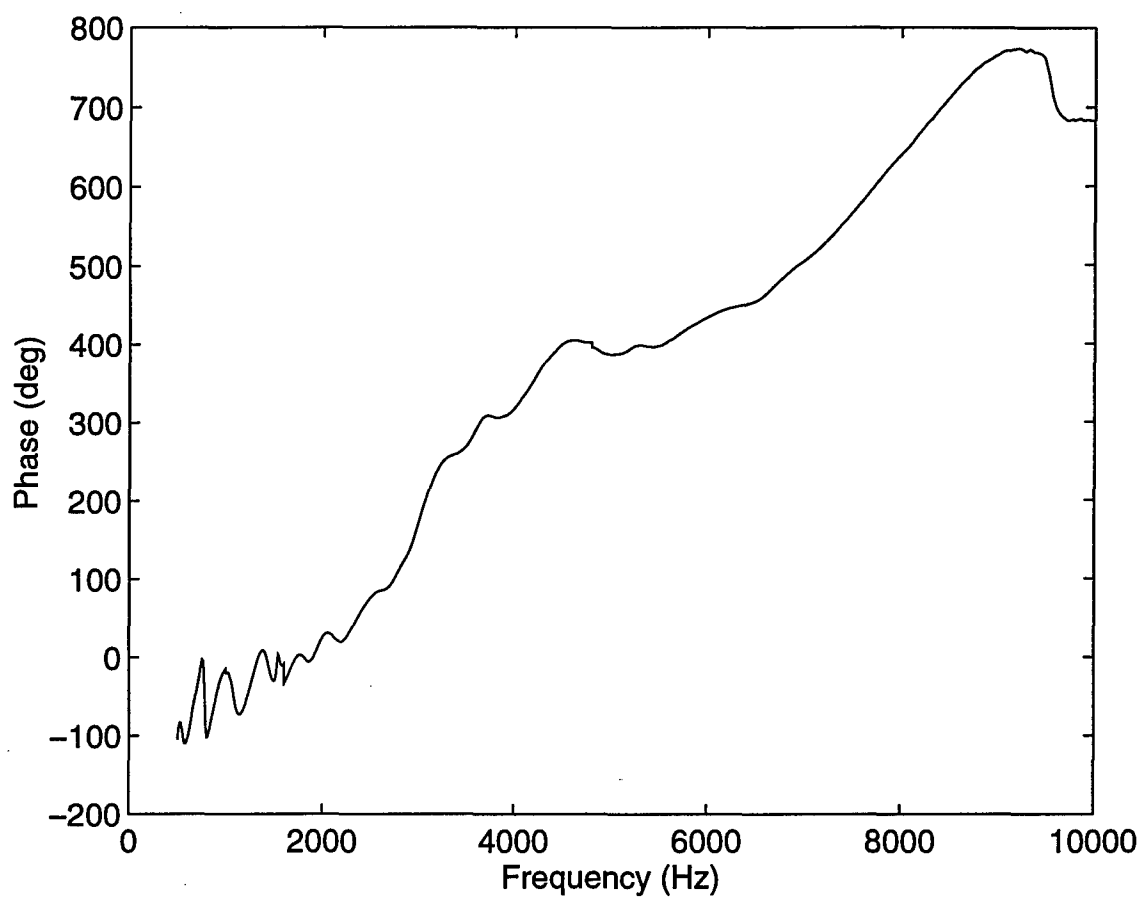
Figure C-9. Phase vs. frequency for fully saturated soil at 86% compaction. Phase is relative between two sensors spaced 5 in. (0.127 m) apart.

Figure C-10. Sensor amplitude vs. frequency for fully saturated soil at 93% compaction. The dashed line indicates the sensor located 1 in. from the soil surface. The solid line indicates the sensor located 6 in. from the soil surface.

Figure C-11. Attenuation vs. frequency for fully saturated soil at 93% compaction. Attenuation is relative between two sensors spaced 5 in. (0.127 m) apart.

Figure C-12. Phase vs. frequency for fully saturated soil at 93%
compaction. Phase is relative between two sensors spaced 5 in. (0.127 m)
apart.